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13.4 All-Digital RF Transmitter in 28nm CMOS with Programmable RX-Band Noise Shaping

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The system architecture is depicted in Fig. 1. It is based on direct-conversion RX-band, by using only 10-bit DAC without DPD, calibration or analog filtering. Digital-intensive TX architectures require DPD or calibration [3-5]. This work presents an RF transmitter implementing a fully digital solution to the aforementioned challenge. Instead of digital RF modulator, with the

ΔΣ modulation and mismatch shaping to attenuate the DAC noise at a programmable duplex distance. This solution enables -160dBc/Hz noise in the RX-band, by using only 10-bit DAC without DPD, calibration or analog filtering.

The system architecture is depicted in Fig. 1. It is based on direct-conversion I/Q modulation, but all signal processing is performed in the digital domain, preceding the DAC. The key observation is that a 10-bit oversampling DAC is sufficient to meet the in-band and ACLR performance requirements of 3G/4G mobile radio standards, but fails at achieving low OOB emissions due to excessive unfiltered quantization noise reaching the TX output [6]. Nevertheless, OOB emissions need to be particularly low only at duplex distance, and the quantization noise spectral density can be shaped accordingly. The solution is to use a digital bandpass ΔΣ modulator, with the programmable NTF stopband centered on the RX-band. The performance of multibit ΔΣ modulation is limited by mismatch noise, caused by static amplitude and timing mismatches between DAC conversion cells. Fortunately, mismatch noise can be also spectrally shaped in the digital domain, by employing a bandpass mismatch shaping (MS) encoding scheme. The MS block, illustrated in Fig. 2, encodes the 1-bit signals $C_0, ..., C_{2^X}$ in a pseudorandom fashion, such that the spectrum of each signal is shaped by the same NTF used in the ΔΣ modulator. Hence, by combining the aforementioned techniques, RX-band noise filtering can be accomplished in a fully digital fashion.

Each of the 54 switching blocks in the MS encoders needs an individual sequence generation circuit (Fig. 3), consisting of a programmable digital filter connected in feedback with a special quantizer (SQ). The SQ quantizes the filter output according to the equations in Fig. 2, and can be modeled as additive random error. Therefore, the circuit generates a pseudorandom sequence shaped by the NTF given in Fig. 3. The NTF notch can be centered freely over the Nyquist range by tuning coefficient $\alpha$, providing up to 20dB noise attenuation at the programmed duplex distance.

The MS encoded signals are fed to the digital mixer (DMIX), which performs upconversion to RF carrier $f_c$ in the digital domain. The DMIX block is clocked at 2fc by an externally generated LO signal, and calculates the DAC cell enables $en_{p/en,n}$ with 25% duty-cycle. The DAC is based on a current-steering architecture, where each conversion cell branch is built of a cascaded current source (CS) in series with a switch: A 4 MSB + 6 LSB segmentation approach is adopted, resulting in 28 conversion cells divided into 16 MSB unary and 6 LSB binaries, with the LSB segment double to create redundancy for MS. Because of 25% duty-cycling, the I-DAC is active only during the 0° and 180° LO phases, whereas the Q-DAC is active during the 90° and 270° phases, thus avoiding any cross-interaction between the two signal paths. No overdesigning is needed to achieve linearity better than 10bits, since the effective resolution in the RX-band is improved digitally by the ΔΣ and MS blocks.

The measured output spectrum of a 9MHz CW tone at 900MHz carrier frequency is shown in Fig. 4. At +3dBm output power, the image and LO feedthrough are at -36 and -61dBC respectively. The C3M3 and C3M5 are both below -67dBC, barely visible above the noise floor. Fig. 4 also plots the output spectrum with a +0.9dBm LTE20 signal at 850MHz (Band 20), showing excellent E-UTRA ACLR performance of less than -60dBC.

Fig. 5 combines the results of several RX-band noise measurements, performed with modulated LTE carriers at varying duplex distances from the 850MHz TX band. In order to evaluate the effectiveness of all-digital RX-band noise shaping, each measurement was repeated three times: with ΔΣ and MS bypassed, with only MS bypassed, and with both ΔΣ and MS in use. In the third mode, the averaged RX-band noise is between -155 and -163dBC, showing up to 20dB improvement when compared to the first two modes. The results are worst at 45 and 80 MHz duplex distances, due to intermodulation with the fc/16 memory internal clock. The notch center frequency is not restricted to the measured duplex distances, but can be freely tuned within ±447.5MHz of the 895MHz carrier frequency.

Fig. 6 compares the TX performance with previous implementations. This work stands out for its superior linearity and compact die area, while exhibiting state-of-art overall performance. Enabled by the low cost of DSP logic in modern CMOS processes, the TX demonstrates the feasibility of all-digital RX-band noise filtering, requiring only 10-bit DAC to achieve -160dBc/Hz noise without need for DPD, calibration or analog filtering.

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References:
Figure 13.4.1: Block diagram of the transmitter.

Figure 13.4.2: Tree structure encoder used in the mismatch shaping (MS) block.

Figure 13.4.3: Implementation details of the noise shaping sequence generator used in the MS encoder.

Figure 13.4.4: Measured spectra for a 9MHz CW tone at fc=900MHz, and an LTE20 signal at fc=850MHz (Band 20).

Figure 13.4.5: Measurement of RX-band noise at various duplex distances, repeated for different LTE signals and bypass modes.

Figure 13.4.6: Performance summary compared with the state-of-art.
Figure 13.4.7: Die micrograph.